A Simple Method of Correcting Magnitudes for the Errors Introduced by Atmospheric Refraction

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ABSTRACT

We show that the errors due to atmospheric refraction are present in the magnitudes determined with the Difference Images Analysis method. In case of single, unblended stars the size of the effect agrees with the theoretical prediction. But when the blending is strong, what is quite common in a dense field, then the effect of atmospheric refraction can be strongly amplified to the extent that some cases of apparently variable stars with largest amplitudes of variations are solely due to refraction. We present a simple method of correcting for this kind of errors.

It is generally known, that atmospheric refraction is a source of serious problems when one is doing astrometry (Evans and Irvin 1995 and references therein). The refraction shifts positions of observed stars toward the zenith, and as it is color dependent the resulting shifts of stars of different colors are different.

The photometry is much less affected by refraction. Usually, a measurement of stellar magnitude is performed by three parameter fit of the stellar image to a known point spread function. Beside the magnitude that is the main objective of the measurement, two angular coordinates are also determined. An accompanying determination of the image position absorbs the effect of atmospheric refraction. The image position is shifted but the resulting value of magnitude is unaffected. In fact it is almost unaffected. The refraction causes the point spread function to be elongated in the direction toward the zenith. When the field size is large then the zenith distance varies and the degree of the PSF elongation is changing when moving across the field. This can be handled by using any position dependent point spread function technique what in the case of large fields is usually necessary for other reasons anyway. There could also be some tiny dependence of the point spread function itself on spectral energy distribution of measured objects. An unresolved binary composed of stars with much different spectral types should have the point spread function more elongated in the direction to the zenith compared to the normal case of a single star. But such an effect of point spread function distortion should be

small, unless the zenith distance is very large, and we are not aware of any attempt of taking it into account.

The determination of angular coordinates that accompany the measurement of magnitude is a must when we use a single picture of a particular field. The coordinates are unknown and they have to be determined. The situation is different when we are investigating stellar variability using large number of CCD frames. Then, it is tempting when measuring magnitudes to use the fixed values for positions and to determine only a single parameter – the magnitude. In this way we obtain an improvement in accuracy, as we get rid of additional degrees of freedom, and eventually have only one degree of freedom instead of three. In such a case the catalog of objects with – presumably – accurate positions has to be prepared beforehand based on a stacked average of frames or by averaging positions resulting from measurements of several frames. The use of the fixed values for coordinates may be even enforced at most cases of application of the image subtraction techniques.

However, when magnitudes are determined for many epochs using fixed coordinates, then the values of resulting magnitudes are affected by movements of the apparent images. The object may move because it has sufficiently large proper motion or trigonometric parallax. It may also move due to color dependent atmospheric refraction. Since the introduction of the Difference Image Analysis the role of the refraction in the magnitude determination process has been often discussed (Tomaney and Crotts 1996, Melchior *et al.* 1999, Alcock *et al.* 1999, Eyer and Woźniak 2001).

The set of OGLE-III observations used for finding transit candidates (Udalski *et al.* 2002) can serve as an example of the image subtraction photometry with enforced fixed values for coordinates. In this case all stars have been photometered on each frame because the effect that was looked for was of a very small amplitude. And that was possible only with the use of an input catalog of fixed positions. This OGLE-III set is also exceptional by attaining relatively high accuracy what is uncommon for a mass survey work. This high accuracy in such kind of data made it possible to look for tiny systematic errors. In the remainder of this paper we shall show, based on the OGLE-III data, how to remove the disturbing influence of the differential refraction effect. In our calculations we have used only a small fraction of this OGLE-III data set, namely 5300 stars from the first chip of BLG100 field.

At first we have to estimate the expected size of the effect. We have done it in a rough way seeking only an order of magnitude estimate. As a starting point we selected 11 values of effective temperature spaced logarithmically in the range from 3000 K to 30 000 K. For each value of temperature a table of relative intensities was prepared as a function of wavelength according to the Planck function. This table was folded with sensitivity curves for the V and I filters and then folded again with the wavelength dependent refraction coefficient. As a result, we have obtained a set of refraction shifts in the filter I as a function of color index $V-I$. The outcome can be summarized as 0.01 arcsec difference for one magnitude difference in $V-I$ color when observations are obtained at the zenith distance equal to 45 degree. This, in case of the OGLE-III data,

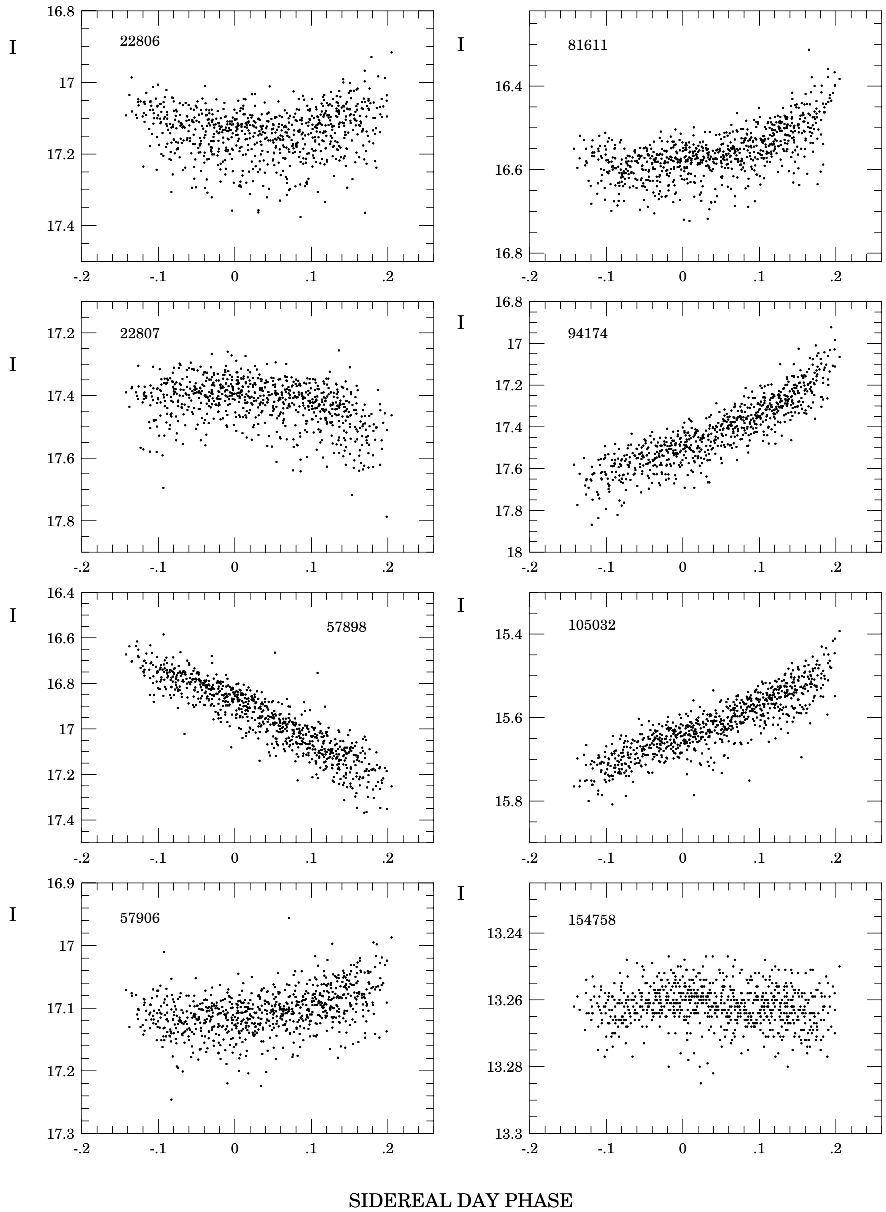

Fig. 1. The dependence of I magnitude on the phase of sidereal day for a set of eight stars. The zero phase corresponds to the moment of the upper culmination of the field center.

corresponds to 0.04 fraction of a pixel and in the case of sub-arcsecond seeing conditions may lead to a few millimagnitudes errors in measured magnitudes.

Next we looked into the data in order to see how the observations are affected by the differential refraction effect. For this purpose we phased observations of individual stars with the sidereal day period. Well observed, unblended, constant stars with a color that is different from the average color should show an expected dependence of magnitude on sidereal day phase. Fig. 1 presents a set of well expressed dependences for eight stars. The zero phase corresponds to the moment of the upper culmination of the field center. Only the brightest among the stars in Fig. 1 can be considered unblended. This can apply to the star 154758 which shows the expected size of the atmospheric refraction effect. For all the other fainter stars, among those pictured in Fig. 1, it turns out that the effect of differential refraction is very strong, much stronger than expected, when there is a bright neighbor whose position is shifted by refraction. Small relative shifts in the neighbor position are changing the degree of blending, thus influencing the photometry of the fainter component. An example of blended objects is a pair of two first stars in Fig. 1 namely 22806 and 22807, whose positions are 10 pixels apart and there is another brighter star situated roughly in the middle of them. In the all remaining five cases there are brighter components closer than 4.5 pixels or $1\overset{\prime\prime}{.}1$.

The visual inspection of many plots like those presented in Fig. 1 led us to the conclusion that a sufficient description of the data can be accomplished with the help of a third degree polynomial

$$m(h) = m_0 + a_1 h + a_2 h^2 + a_3 h^3 = m_0 + r(h) \tag{1}$$

where h is an hour angle expressed in units of the sidereal day length, $m(h)$ is a stellar magnitude as a function of an hour angle, m_0 is the value of magnitude at the moment of the upper culmination, and the coefficients a_1, a_2, and a_3 are to be determined by the least squares fit to observations.

A signature of the differential refraction can be also traced in periodograms. We have calculated an average of periodograms for 200 bright, accurately observed, non-variable stars. As expected, this average shows peaks positioned at frequencies that are multiples of the sidereal day frequency. The average periodogram based on uncorrected data is plotted in the upper panel of Fig. 2. Next, from the magnitudes of each of these 200 stars we subtracted the fitted third order polynomial $r(h)$ defined in Eq. (1), calculated periodograms for individual stars and then an average periodogram. This average periodogram is plotted in the middle panel of Fig. 2. The peaks related to differential refraction disappear. The periodogram has zero values at frequencies exactly equal to multiple values of the sidereal day frequency. However, there is a raised level of noise around each of these zero values. The values of periodogram at frequencies close to zero are also higher than average. This is what is used to be called a red colored noise. Even seemingly constant stars may exhibit low amplitude oscillations with periods longer than 5 days. Another source of this excess of low frequency noise may be due to non negligible shifts connected with proper motions. In

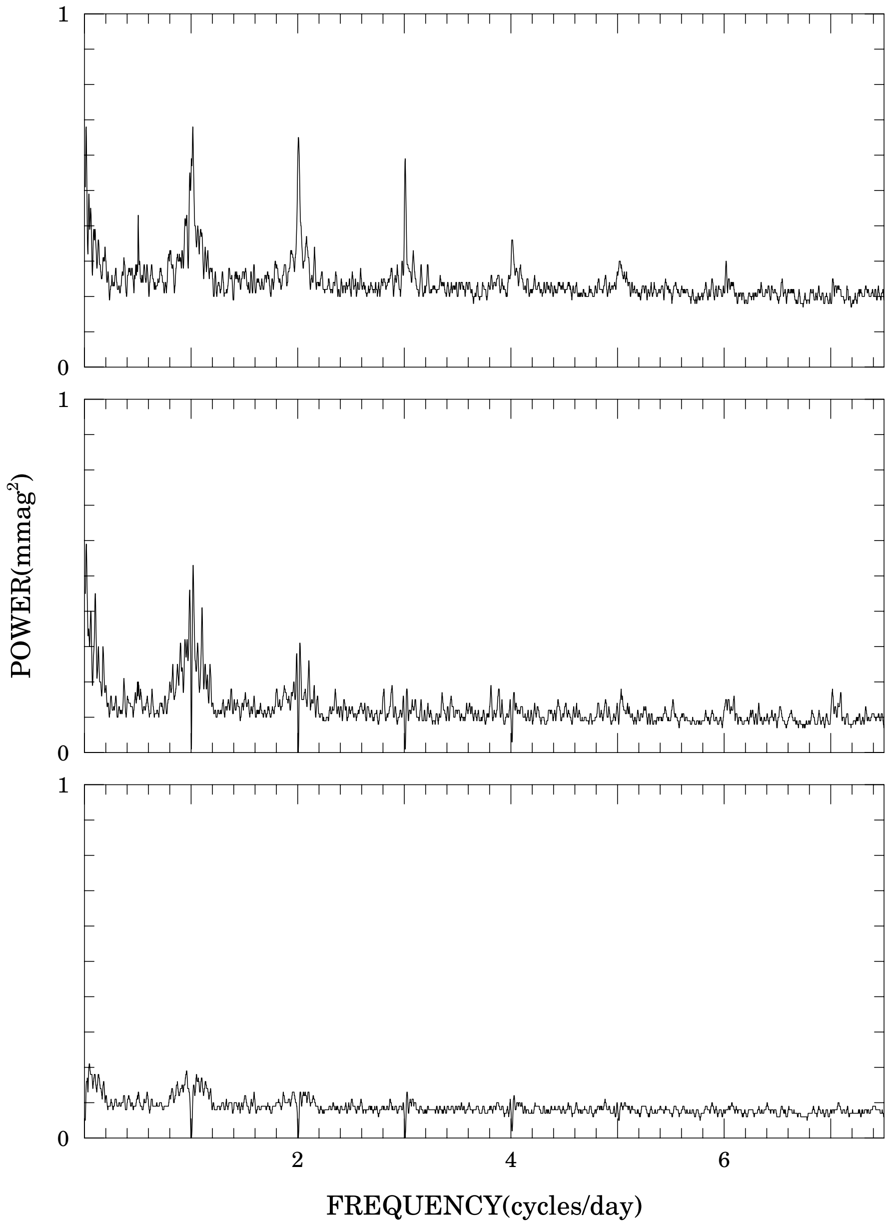

Fig. 2. The average periodogram for 200 bright, non-variable stars from the investigated field. The upper panel presents the periodogram, based on uncorrected data. The middle panel shows the average periodogram after correcting the observations of individual stars for refraction according to Eq. (1), the lower panel presents the periodogram based on the observations corrected according to Eq. (2).

order to limit this excess of low frequency noise we performed another fit to individual stars. This time beside the third degree polynomial with respect to the sidereal day phase we have included also a third degree polynomial with respect to time according to the formula

$$m(h,t) = m_0 + r(h) + b_1(t - t_0) + b_2(t - t_0)^2 + b_3(t - t_0)^3 \qquad (2)$$

which is Eq. (1) extended by adding to it three new terms with up to the third power of the quantity $(t - t_0)$ where t is mid-exposure time and t_0 is conveniently chosen to be an average of all mid-exposure times.

The average of periodograms of the 200 stars calculated after the fit according to Eq. (2) was subtracted from the raw observations is presented in the lower panel of Fig. 2. We can see that subtraction of the contribution from the differential refraction according to Eq. (2) not only removes the peaks that originate from the differential refraction but also brings down the noise level and therefore makes it possible to detect variability of smaller amplitude.

Usually any improvement has some price, sometimes in an unexpected form. Also in this case the procedure that causes an improvement for majority of objects may produce undesirable artifacts for some other objects. Of course it is commensurability between the sidereal day and a period of variability of a particular object that is a source of troubles. If the period of variability is in an exact resonance with the sidereal day then the situation is hopeless. Simply, we cannot detect such variability. In fact it is not much worrying. In the case of exact resonance, the observations cover only limited range of variability phases simply because they cover only limited range of sidereal day phases and therefore it is difficult to make a unique determination of the variability characteristics anyway.

Let us consider a more common case when we are only close to the commensurability. We shall show that in such a case the damage made by the removal of differential refraction effect can be repaired. As an example of such object we take the star 143483. It is an eclipsing binary with the period of 0.66695 day so that we are very close to the 2:3 resonance.

Fig. 3 shows in its uppermost panel (a) the eclipsing light curve using uncorrected observations. Panel (b) of Fig. 3 shows the same light curve but after the differential refraction correction was applied according to Eq. (1). We can see the disastrous effect of the corrections. Two periods are so close to commensurability that the light variability due to eclipses produces spurious detection of the differential refraction effect. This happens when we force the fit to the formula that contains the terms $r(h)$ connected with the differential refraction only. It is different when we add to the fit also harmonic terms being functions of the phase θ of the eclipsing variations cycle and then subtract from the observations only $r(h)$.

$$\begin{aligned} m(h,\theta) \quad &= \quad m_0 + r(h) + c_0 \cos(2\pi\theta) + d_0 \sin(2\pi\theta) \\ &\quad + \sum_{k=1}^{n} [c_k \cos(4k\pi\theta) + d_k \sin(4k\pi\theta)]. \qquad (3) \end{aligned}$$

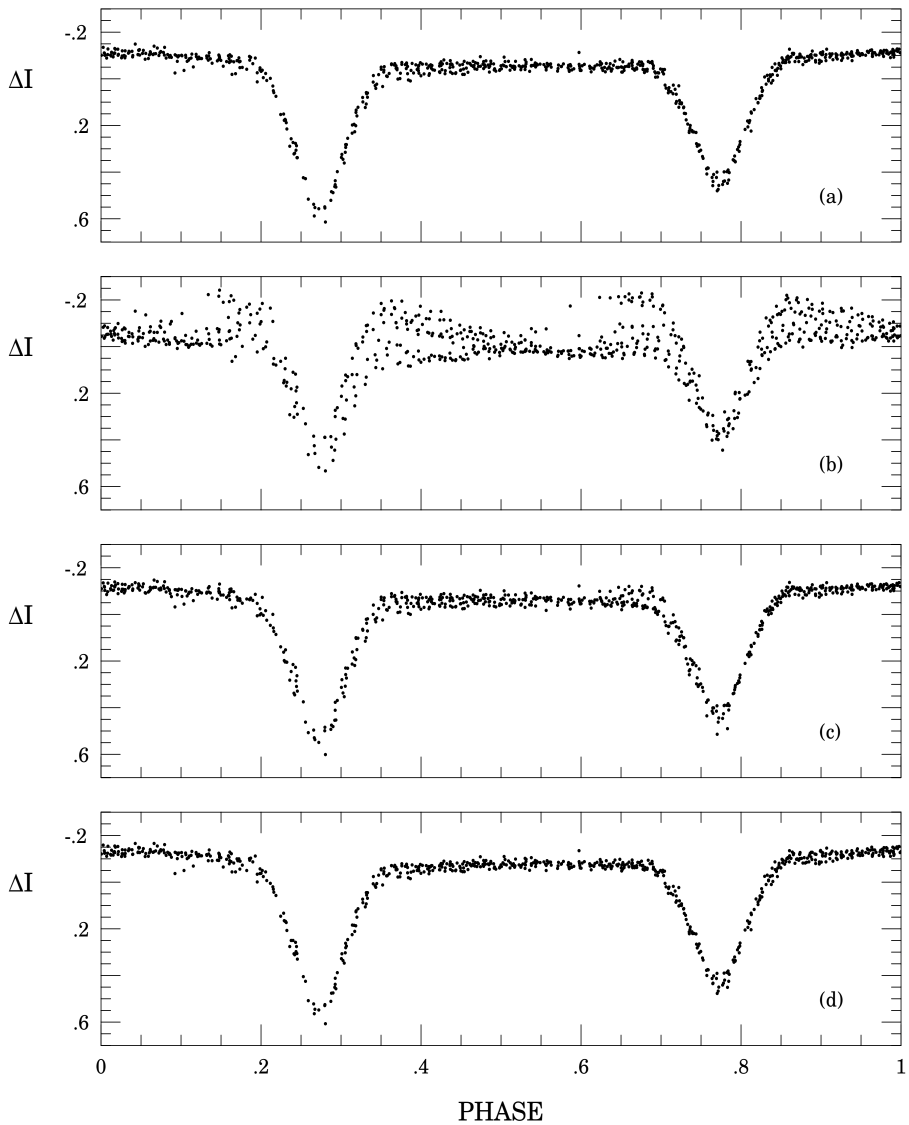

Fig. 3. Observations of eclipsing binary 143483. ΔI denotes the deviation of I magnitude of the star from the mean value. The uppermost panel (a) shows the raw data uncorrected for refraction. Three remaining panels present the observations corrected for refraction. Panel (b) corresponds to the case when calculating the corrections only the polynomial describing refraction was fitted to the observations according to Eq. (1). Panels (c) and (d) correspond to the situation, when calculating the refraction a sinusoid with the orbital period was fitted simultaneously to the observations according to Eq. (3). Panel (c) is for the case when a sinusoid with the orbital period and its first overtone was fitted, and panel (d) for the case when first five even overtones of the orbital period were taken into account.

Panels (c) and (d) of Fig. 3 show the resulting light curves obtained with different numbers of harmonic expansions terms. The number of terms n is equal to one in panel (c) and it is equal to five in the case of panel (d).

We can conclude that when dealing with observations made with the use of the I filter the atmospheric refraction effect is small and comparable with observational errors in the case of bright, isolated, well observed stars. It can be, however, dominating in the case of faint objects blended with a bright component.

The atmospheric refraction is absent outside of the Earth atmosphere. Hopefully it can be also eliminated on the observation stage in case of ground-base observations. A device planned for VLT Survey Telescope and described in (Kuijken 2002) should do the job. We should remember however that we cannot get away from the disturbing effects of proper motions or parallaxes by using any intelligent device or by putting telescopes into space.

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